CSIRO PUBLISHING
www.publish.csiro.au/journals/ajsr *Australian Journal of Soil Research,* 2009, **47**, 198–205

Soil respiration and N_2O emission in croplands under different ploughing practices: a case study in south-east China

Shutao Chen[A,C,D] *and Yao Huang*[B]

[A]School of Environmental Science and Engineering, Nanjing University of Information Science and Technology, Nanjing 210044, China.
[B]Laboratory of Atmospheric Physics and Chemistry (LAPC), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China.
[C]College of Resources and Environmental Sciences, Nanjing Agricultural University, Nanjing 210095, China.
[D]Corresponding author. Email: Chenstyf@yahoo.com.cn

Abstract. Studies on the CO_2 and N_2O emission patterns of agricultural soils under different ploughing practices may provide an insight into the potential and magnitude of CO_2 and N_2O mitigation in highly managed farmland soils. In this study, field measurements of soil respiration and N_2O flux with different ploughing depths were performed in the 2003–04 wheat (*Triticum aestivum* L.), 2004 maize (*Zea mays* L.), and 2004–05 wheat seasons. Soil temperature and moisture were simultaneously measured. Results showed that, in each cropping season, the seasonal variation in soil respiration developed with a similar pattern for different treatments, which was primarily regulated by soil temperature. This work demonstrates that ploughing depth can influence long-term loss of carbon from soil, but this was contingent on preceding cropping types. Given the same preceding cropping practice, no significant difference in N_2O emission was found among different ploughing depths in each cropping season.

Additional keywords: soil respiration, N_2O emission, ploughing practice, soil temperature, soil moisture.

Introduction

Second to gross photosynthesis, carbon dioxide (CO_2) emissions from soils (i.e. soil respiration) exceed all other terrestrial–atmospheric carbon exchanges (Raich and Schlesinger 1992). Increases in soil CO_2 emissions have the potential to exacerbate increasing atmospheric CO_2 levels and to provide a positive feedback to global warming (Raich and Tufekcioglu 2000). Nitrous oxide (N_2O) is another important trace gas that contributes to global warming (Yung *et al.* 1976) and the depletion of stratospheric ozone, which acts as a shield from damaging ultraviolet-B radiation (Crutzen 1970). The atmospheric concentration of N_2O continues to rise at a rate of approximate 0.26% per year and has reached a concentration of 319 ppbv (10^{-9} mol/mol) in 2005 (IPCC 2007).

Agricultural management practices are known to influence CO_2 emission (IPCC 2007). The ability to increase soil organic C by proper ploughing and erosion management provides long-term justification for soil conservation programs (Hunt 1996; Weinhold and Halvorson 1998). There is interest in the potential and magnitude of highly managed agricultural soils to reduce CO_2 emission, and conservation tillage (e.g. no-till or reduced tillage) can increase C storage (Lal *et al.* 1999). Deep tillage often causes an immediate loss of soil CO_2 when the soil is inverted and fractured, and it also incorporates plant residues and aerates the soil, thus enhancing microbial oxidation (Reicosky and Lindstrom 1993; Gesch *et al.* 2007). However, insights into seasonal or yearly soil respiration patterns as affected by degree of disturbance (different ploughing depths) are rare (Mosier *et al.* 2006; Oorts *et al.* 2007).

The N_2O emissions from farmland are normally associated with N (as fertiliser or manure) application under wet conditions near the soil surface (Arah *et al.* 1991; Clayton *et al.* 1994; Ball *et al.* 1999). The production, consumption, and transport of N_2O are strongly influenced by changes in soil structural quality associated with tillage practices (Ball *et al.* 1999; Carmo *et al.* 2007). Aulakh *et al.* (1984) and Ball *et al.* (1999) found that gaseous losses of N were higher under no-till than under conventionally tilled systems. However, Arah *et al.* (1991) found very low emissions under long-term no-tillage near to the tillage experiment on similar soil. A field study conducted at Nyabeda, western Kenya Highlands, showed that emissions of N_2O over 99 days were greater from tilled than from no-till treatments (Baggs *et al.* 2006). Liu *et al.* (2005) reported that no-till did not significantly increase N_2O emission compared with conventional ploughing in a 2-year experiment in north-eastern Colorado, USA. Above all, these studies have produced inconsistent results regarding the effect of ploughing practice on N_2O emissions. In addition, reduced ploughing effects on

10.1071/SR07225 0004-9573/09/020198

N_2O and CO_2 fluxes from fertilised agricultural soils are seldom examined; particularly lacking are the seasonal or yearly field measurement data of N_2O and CO_2 emissions.

Before the early 1980s, deep ploughing was commonly adopted for seedbed preparation, stubble incorporation, and weed control in croplands in China (He *et al.* 2007). By contrast, alternative agricultural practices reducing disturbance in agro-ecosystems have been developed over the last 20 years, and are currently practiced in many provinces in China (He *et al.* 2007). Since the early 1990s, ~20 Mha of farmland has been placed under reduced tillage in China (Zhang *et al.* 2005), largely under shallow ploughing (~100–150 mm) or no-till practice. Therefore, understanding soil respiration and N_2O emission under different ploughing depths will provide an insight into the impacts of changed ploughing history on greenhouse gases emission.

The objective of this study is to address the effects of ploughing depth and preceding cropping practice on soil CO_2 and N_2O emission. This information will help to optimise agricultural practice to mitigate CO_2 and N_2O emissions from agricultural soils and increase soil C sequestration.

Materials and methods

Site description

In the 2003–05 cropping seasons, field experiments were performed in farmlands at Jiangsu Academy of Agricultural Sciences (32.0°N, 118.8°E), Jiangsu Province, south-east China. Rice (*Oryza sativa* L.) – wheat and maize – wheat rotations represent the main crop production regimes in local area (Huang *et al.* 2007). Shallow ploughing is a common tillage practice for winter wheat and maize in south-eastern China (Wang *et al.* 1985; Pan *et al.* 1986; Huang and Liu 1989; Du 2001; Chen *et al.* 2006). A previous investigation also indicated that the mean value of plough layers for paddy soil in south-eastern China was ~150 mm (Pan *et al.* 2003, 2005). Annual average temperature of the experimental site is 15.6°C and annual rainfall averages ~1100 mm. The soil collected from the experimental field is classified as hydromorphic, consisting of sand 290.7 g/kg, silt 160.0 g/kg, and clay 549.3 g/kg, with an initial pH(H_2O) of 6.1. Total organic C and N contents before the study were 9.7 and 1.1 g/kg, respectively. The bulk density of the soil is 1.3 g/m^3. We measured soil conditions including soil organic matter, N content, pH, and texture after the field experiment. No obvious changes in these soil conditions were detected.

Field experiment

The experimental design is shown in Table 1. A completely randomised plot design was set up and each treatment was replicated 4 times. No-till (0 mm ploughing) and shallow ploughing (120 mm ploughing) treatments were coded as NT and CT, respectively, and the planting seasons were represented by serial number 1, 2, 3, and 4 (Table 1). The 250-mm ploughing treatment was coded as DP. Winter wheat, maize, and winter wheat were planted in the 2003–04, 2004, and 2004–05 seasons, respectively.

Mouldboard plough using 3-bottom plough, 500-mm-wide bottoms, to the 250-mm depth followed by a disk harrow twice was used to create the deep ploughing treatments. This resulted in the same depth and degree of soil disturbance with smaller aggregates and a less porous surface. The shallow ploughing treatments were created by using 3-bottom plough, 400-mm-wide bottoms, to the 120-mm depth followed by a disk harrow twice. No-till treatments represent plots that were left undisturbed during our field experiment period, rather than field plots with a long-term history of no-till. All treatments were shallow-disked for seedbed preparation. No ploughing also involved spraying the sward with paraquat for seedbed preparation.

Table 1. Field experimental design

Growing season	Ploughing depth (mm)	Preceding crop	Treatment code
2003–04 winter wheat	0	Rice	NT1
	120	Rice	CT1
2004 maize	0	Wheat	NT2
	120	Wheat	CT2
2004–05 winter wheat	0	Maize	NT3
	120	Maize	CT3
	0	Rice	NT4
	120	Rice	CT4
	250	Rice	DP

Preceding crop residues were removed from fields, except that root and ~80 mm of stubble of preceding crops were retained in all the treatments. Root and stubble biomass, and C and N content in plant residues for different ploughing treatments are shown in Table 2. Crop stubble was incorporated at the soil depth of 120 and 250 mm for the shallow and deep ploughing treatments, respectively, and it was left on the soil surface for the no-till treatments.

In the 2003–04 and 2004–05 wheat seasons, winter wheat cv. Yangmai 158 was sown on 4 November 2003 and 4 November 2004, respectively. In the 2004 maize season, maize cv. Suyu 1 was sown on 8 June 2004. The main growth stages of wheat and maize are shown in Table 3. During the rapid growth stage, the number of wheat plant tillers/m^2 was 1075, 898, 1826, 1600, 1198, 1081, and 1146 for NT1, CT1, NT3, CT3, NT4, CT4, and

Table 2. Root and stubble biomass (g/m^2), and C and N content (g/kg) of residues

The preceding cropping practice for NT1 and CT1 is rice paddy. Root biomass, stubble biomass, root C content, stubble C content, root N content, and stubble N content for the preceding rice are172 g/m^2, 171 g/m^2, 435 g/kg, 425 g/kg, 10 g/kg, 10 g/kg, respectively. The C and N contents were only determined for CT2 and CT3 treatments in Table 2

Treatments	Root biomass	Stubble biomass	C root	C stubble	N root	N stubble
NT1	118	107				
CT1	123	111				
NT2	163	148				
CT2	166	151	490	468	6	7
NT3	176	160				
CT3	141	128	490	505	7	8
NT4	138	125				
CT4	179	163				
DP	152	139				

Table 3. Main growth stages of wheat and maize

Cropping season	Main growth stages Tillering	Stem elongation	Flowering	Maturing
2003–04 wheat	12 Dec. 2003	10 Mar. 2004	8 Apr. 2004	8 May 2004
2004 maize		9 July 2004	30 July 2004	18 Aug. 2004
2004–05 wheat	7 Dec. 2004	17 Mar. 2005	9 Apr. 2005	8 May 2005

DP, respectively. The planting density of maize is shown in Fig. 1.

Phosphorus as $Ca(H_2PO_4)_2$ and potassium as KCl were applied at the rates of 92 kg P and 118 kg K/ha, respectively, before sowing in each of the 3 experimental seasons. Nitrogen fertiliser (urea) application schedules are indicated in Fig. 2. Nitrogen, P, and K fertilisers were broadcast in each plot.

Gas sampling and analysis

Soil respiration and N_2O fluxes were measured using a closed-chamber technique. Before each cropping season, we set up permanent boardwalks to randomly selected gas emission measurement sites to reduce field disturbance during gas sampling. Base frames made of steel for the gas collection chambers were installed in each plot. Circular base frames (140-mm-diameter) and quadrat base frames (500 mm by 500 mm) were used for gas flux measurements. The equipment used for measuring gas emission over the wheat-growing season was different from that over maize-growing season. In the 2003–04 and 2004–05 wheat seasons, the circular base frames used for soil respiration measurement were set up in the soil between wheat plants (Fig. 1*a*). As wheat root density in the chamber base decreased with increasing chamber diameter, the smaller chamber base size would ensure the root density in the chamber base was closer to that outside of the base. Therefore, we used the circular base with 140 mm diameter and column chamber of 300 mm height to measure soil respiration (including root and heterotrophic respiration) in the wheat plots. The quadrat base frames (500 mm by 500 mm) and cubic chambers (500 mm by 500 mm by 500 mm or 500 mm by 500 mm by 1000 mm) were used for soil–wheat system N_2O emission measurement (Fig. 1*a*). In the 2004 maize-growing season, quadrate base frames instead of circular frames and cubic chambers were used to measure CO_2 and N_2O emissions. The base frames were set up in the soil between 2 rows of maize (Fig. 1*b*). As the distance between 2 rows of maize plant is 600 mm, the maize root density in chamber base is close to that outside the base.

All chambers were wrapped with sponge and stannum foil to prevent temperature exchange. During each sampling, a chamber was placed on the frame, and the chamber was closed when a groove on the top edge of the frame was filled with water. In each treatment, 4 chambers were set up as replicates for a set of flux measurements.

Measurements of soil respiration and N_2O flux were generally made once or twice a week over each season, except that gas samples were taken once a day from 30 October (2 days after ploughing) to 21 November 2003 in the 2003–04 wheat season. In addition, gas samples were taken once every second day for ~2 weeks after ploughing in the 2004 maize and 2004–05 wheat seasons.

Gas samples were analysed by a modified gas chromatograph (Agilent 4890D) equipped with flame ionisation detector (FID) and electron capture detector (ECD) (Wang and Wang 2003). Carbon dioxide was reduced by hydrogen to CH_4 in a nickel catalytic converter at 375°C, and further detected by FID. The oven was operated at 55°C, and the FID and ECD were at 200°C and 330°C, respectively. The soil respiration rate or N_2O flux was determined from the slope of the gas concentration change

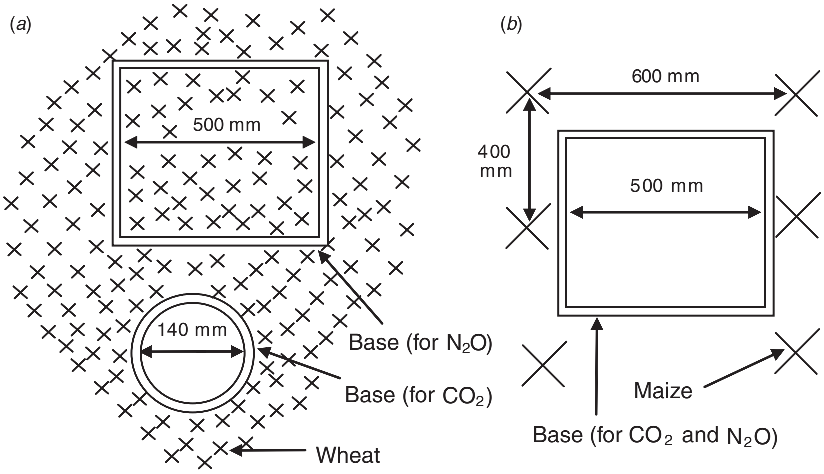

Fig. 1. Schematic drawing of chamber base for gas sampling in (*a*) winter wheat and (*b*) maize plots.

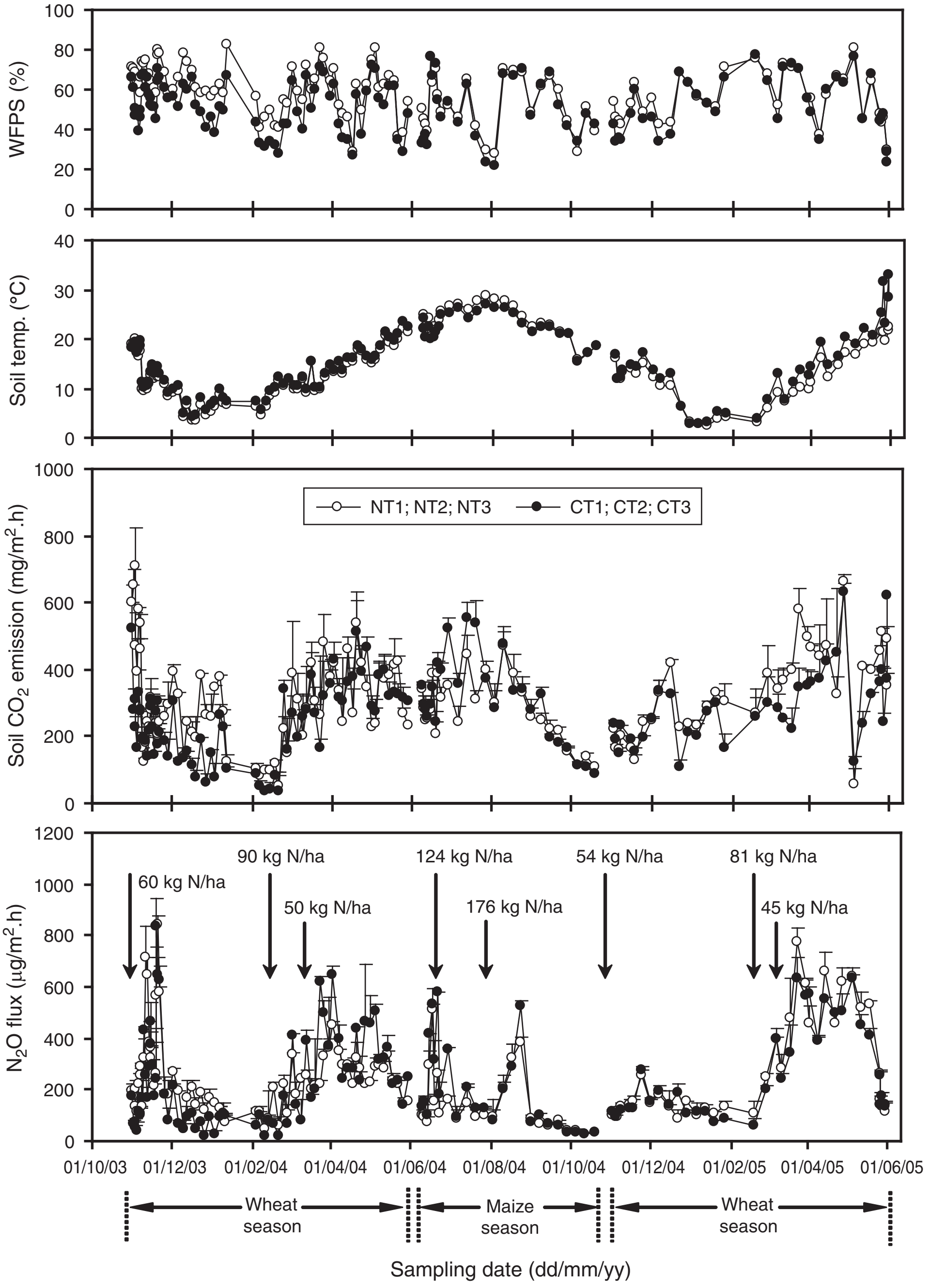

Fig. 2. Seasonal variations of soil moisture, soil temperature, soil respiration rates, and N_2O fluxes (NT1, NT2, NT3 and CT1, CT2, CT3 from 2003 to 2005). Vertical bars represent standard errors of the means.

in the 3 samples taken at 0, 10, and 20 min after closing the chamber. Almost all samples sets yielded linear regression values of $R^2 > 0.998$ for soil respiration and $R^2 > 0.90$ for N_2O flux.

Measurements of soil temperature and moisture

Soil temperature and moisture were measured at the time of gas sampling. The soil temperature at 100 mm depth was automatically recorded using an Optic Stowaway Temp Logger (Onset Computer Corporation, USA) over the experimental seasons. Soil moisture (volumetric water content) at 100 mm depth was measured by MPM-160 (TDR) made by Jiangsu Academy of Agricultural Sciences, China. Soil water content (v/v) was then expressed as WFPS (water filled pore space) values according to bulk density.

Data analyses

In each cropping season, seasonal amounts of soil respiration and N_2O emissions were calculated by multiplying the average flux of 2 consecutive measurements by the intervals between these 2 measurements. Seasonal mean soil respiration rates and

N_2O fluxes were obtained by dividing the seasonal total cumulative gas emission by the experimental days. Average fluxes and standard errors were calculated based on 4 replicated measurements. The difference of gas emission among the treatments was analysed using 1-way ANOVA in SPSS 11.0.

Results

Seasonal variations in soil moisture, temperature

Relative to the no ploughing treatments, ploughing decreased soil water content (Fig. 2*a*, Table 4). Soil water content was, on average, ~20.0% higher for NT1 than for CT1 over the 2003–04 wheat season. Similarly, relative to the CT2 treatments, soil water content in the NT2 treatments was ~5.4% higher over the 2004 maize season. In the 2004–05 wheat-growing season, NT4 produced the highest soil moisture with a seasonal mean value of 57.2% (Table 4). Soil temperature (Fig. 2*b*) showed strong seasonal patterns that followed local seasonal variation in air temperature. Seasonal mean soil temperature was 0.7°C higher for CT1 than for NT1 over the 2003–04 wheat season, while it was 1°C higher for NT2 than for CT2 over the 2004 maize season. Soil temperature was 12.2, 14.6, 13.8, 12.9, and 14.9°C for NT3, CT3, NT4, CT4, and DP, respectively, in the 2004–05 wheat season (Table 4).

Seasonal variations in soil respiration

The seasonal variation in soil respiration developed with a similar pattern for different treatments in each growing season (Fig. 2*c*), generally associated with the change of soil temperature. However, the dynamics of soil temperature was not consistent with that of soil respiration from sowing to the over-wintering period in the 2004–05 wheat season. A sharp decrease in soil respiration was observed on 4 May 2005, probably due to the decrease in soil temperature and dramatic increase in soil water content.

Ploughing effects on soil respiration varied in different cropping seasons and crop growth periods. Soil respiration rate was slightly lower for the deep ploughing treatments than for the no ploughing plots from sowing to over-wintering in the 2003–04 wheat season and from turning green to the elongation period in the 2004–05 wheat season (Fig. 2*c*). Over the entire 2004–05 wheat-growing season, no ploughing showed a higher soil respiration rate than the 120-mm ploughing (Fig. 2*c*). In the 2004 maize-growing season, an obvious difference in soil respiration was found between NT2 and CT2 during the period mid-June to mid-July (Fig. 2*c*) when maize grew rapidly.

Table 4. Seasonal mean moisture and temperature for different treatments

The *t*-test was performed in the 2003–04 wheat season, 2004 maize season, and 2004–05 wheat season, respectively. Within each season and parameter, means followed by the same letter are not significantly different ($P > 0.05$) among different ploughing treatments

Season	Code	Moisture (%)	Temperature (°C)
2003–04	NT1	62.0a	12.4a
	CT1	52.1b	13.1b
2004	NT2	52.5a	23.6a
	CT2	49.9b	22.6b
2004–05	NT3	55.4a	12.0a
	CT3	52.4b	14.6b
	NT4	57.2c	13.8bc
	CT4	53.7b	12.9ad
	DP	53.0b	14.9e

Seasonal variations in N_2O emissions

Nitrous oxide fluxes as affected by N fertilisation, ploughing, and soil moisture are shown in Fig. 2*d*. In general, seasonal variation of N_2O emission developed with a similar pattern for different treatments in each season. In 2003, N_2O emissions increased quickly with N fertilisation and ploughing operation. An emission peak appeared ~2 weeks after fertilisation. The sharp increase in N_2O emissions from late February to April was probably induced by spring thaw due to the warmer soil temperatures (Fig. 2*a*, *b*) and applications of N fertiliser in February and March 2004. In the 2004 maize-growing season, N_2O emissions increased quickly with N application and sharp increase in soil moisture due to precipitation in late June and late August 2004 (Fig. 2*a*). N_2O emission in the 2004–05 wheat-growing season generally exhibited similar seasonal dynamic patterns to that in the 2003–04 wheat-growing season (Fig. 2*d*).

An effect of ploughing on N_2O emission was not obvious (Fig. 2*d*). The difference in N_2O emission among the no-ploughing, shallow-ploughing, and deep-ploughing treatments was not observed in each cropping season.

Comparison of CO_2 and N_2O emission rates under different ploughing regimes

The influence of preceding cropping practice and ploughing depth on soil respiration is shown by the measured seasonal mean respiration rates in Table 5. ANOVA showed that the effect of ploughing depth on soil respiration was dependent on preceding cropping practice. Over the 2003–04 and 2004–05 wheat-growing seasons (both of their preceding cropping practices were paddy rice), mean soil respiration rates were not significantly different ($P > 0.05$) for no ploughing and shallow ploughing treatments. The shallow ploughing treatment of CT2 led to greater soil CO_2 loss than the no ploughing treatment of NT2 in 2004 maize-growing season; however, significantly higher ($P < 0.05$) soil respiration rates occurred with the no-ploughing treatment of NT3 in the following 2004–05 wheat-growing season. Seasonal average CO_2 emission rate was greatest in the NT3 treatments in the 2004–05 wheat-growing season, which could be explained by the decay of crop residues (maize stubble).

As shown in Table 5, no significant difference ($P > 0.05$) in the seasonal mean N_2O fluxes was observed between the treatments of NT1 and CT1 in the 2003–04 wheat-growing season. No ploughing also did not lead to significantly larger N_2O flux than shallow ploughing in the 2004 maize-growing season. Among all the treatments, only seasonal mean N_2O flux was significantly higher for NT3 than for CT4 in the 2004–05 wheat-growing season.

Nitrogen emission factor (EF) for N_2O, the proportion of fertiliser N released as N_2O-N, was calculated by the difference between seasonal N_2O emissions from fertilised and no-fertilised plots (Table 5). The lowest EF value (1.52%) occurred for the CT1 in the 2003–04 season. The NT3

Table 5. Seasonal mean soil respiration rates and N_2O fluxes for different treatments

One-way ANOVA analysis was performed in the 2003–04 wheat, 2004 maize, and 2004–05 wheat seasons, respectively. Within each season and parameter, means followed by the same letter are not significantly different ($P > 0.05$) among different ploughing treatments. s.e., Standard error; EF, emission factor of nitrogen for N_2O, calculated by the difference between seasonal N_2O emissions from fertilised plots and unfertilised plots. Seasonal N_2O emissions from unfertilised plots in the 2003–04 and 2004–05 wheat seasons were 3.82 and 4.32 kg N/ha, respectively. No unfertilised plots were set up in the 2004 maize season

Season	Code	CO_2 (mg/m^2.h)		N_2O (μg/m^2.h)		N_2O EF
		Mean	s.e.	Mean	s.e.	(%)
2003–04	NT1	243.3a	12.8	220.0a	4.6	1.54
	CT1	204.8a	13.1	216.0a	20.7	1.52
2004	NT2	316.8a	12.2	131.8a	14.4	
	CT2	359.3b	7.6	165.9a	4.1	
2004–05	NT3	307.1b	13.7	291.3a	7.8	2.77
	CT3	241.0a	13.7	264.1ab	12.8	2.33
	NT4	243.8a	6.0	267.5ab	10.8	2.35
	CT4	276.9b	12.3	257.8b	12.5	2.15
	DP	279.3b	5.9	261.0ab	5.5	2.23

treatment produced the highest EF value (2.77%) in the 2004–05 season. By keeping the N addition constant, the EF value depended on management practice (ploughing practice and preceding cropping regime) (Table 5). For example, when N was applied at the rate of 180 kg N/ha in the 2004–05 season, the EF value ranged from 2.15% in the CT4 treatment to 2.77% in the NT3 treatment, and this range was due to the differences in preceding crop regime and ploughing depth. Although the CT1 and CT4 treatments had similar N addition and management practice, the EF value was 1.52% and 2.15% in these 2 treatments, respectively, suggesting an inter-annual variation in the EF (Table 5).

Discussion

Effect of ploughing practice on soil respiration

Conservation tillage has been conceived as a practice to effectively mitigate C losses from agricultural soils. On the contrary, intensive tillage methods often increase the CO_2 evolution from soils (Reicosky and Lindstrom 1993; Alvarez *et al.* 1995, 2001) through enhanced biological oxidation of soil C by increasing subsequent microbial activity (Reicosky *et al.* 1997). High CO_2 fluxes are generally associated with soil disturbance that result in a rougher surface (Reicosky and Lindstrom 1993; Ball *et al.* 1999; Reicosky and Archer 2007). Franzluebbers *et al.* (1995) showed that soil respiration was less for a no-ploughing treatment than a ploughing treatment with 200–250 mm depth during the wheat season, but greater for no ploughing than for shallow ploughing with 100–150 mm depth during a soybean (*Glycine max* L.) season. However, Baggs *et al.* (2006) found that a no-ploughing practice of *Tephrosia* residues added had no significant effect on emissions of CO_2 compared with conventional tillage. Our result showed that, compared with no ploughing practice, intensive ploughing (250 mm depth) increased soil respiration significantly in wheat farmland (whose preceding cropping practice was paddy rice). Our study supports the result of Morris *et al.* (2004) and Gesch *et al.* (2007) showing that relative to deep tillage, no-tillage may reduce soil CO_2 flux and soil oxidation potential of organic soils.

It is well documented that soil respiration differing with different tillage practices was related to previous tillage history, soil organic C concentration, surface residue, soil texture, and climate condition (e.g. rainfall) (Reicosky *et al.* 1997; Ball *et al.* 1999; Alvarez *et al.* 2001). Indeed, our study indicated that preceding cropping practice also influenced soil respiration over the following cropping season. The effect of shallow ploughing on soil CO_2 emissions was contingent on preceding cropping practice. Preceding cropping practice represents the quality and quantity of crop residues and soil water condition which maybe influence the soil CO_2 production and emission in the following season. For example, crop residue C : N ratio plays an important role in soil CO_2 emissions (Huang *et al.* 2004). Silver and Miya (2001) found that the root decay constant (year^{-1}) was significantly negatively correlated with root C : N ratio when they analysed a total of 175 datasets from the literature. Moreover, ploughing practice caused different quantity of crop residues. Except for CT3, root and stubble biomass was higher for shallow ploughing treatments than no-till treatments (Table 2), which agreed with some previous investigations (Malhi *et al.* 2006; Chatskikh and Olesen 2007). Higher residue production was in accordance with higher soil respiration rate for the maize-planted farmland (Tables 2 and 5). Soil respiration rate was also associated with the biomass of winter wheat root and stubble biomass. Generally, higher residue production was accompanied by higher CO_2 emission rate (Tables 2 and 5). This might be due to the intensive influence of plant growth and root biomass on soil respiration (Chen and Huang 2006; Jia *et al.* 2006; Kuzyakov 2006). The comprehensive impact mode and mechanisms of residue quality and quantity, management regimes in preceding season, and ploughing method in current season on soil CO_2 emission needs to be further investigated.

Effect of ploughing practice on N_2O emission

The range of cumulative N_2O emission values are consistent with those reported in other studies conducted under similar environmental conditions (Zheng *et al.* 2004; Zou *et al.* 2005). Cumulative N_2O loss was not influenced by tillage system in the 2003–04 or 2004 seasons (Table 5). Similar emissions from no-till and shallow ploughing or deep ploughing are contrary to the results from many other regions (Aulakh *et al.* 1984; Arah *et al.* 1991; MacKenzie *et al.* 1997; Ball *et al.* 1999), but are in agreement with some recent studies (Kaharabata *et al.* 2003; Helgason *et al.* 2005; Liu *et al.* 2005).

These inconsistent results could be attributed to the great variation of field N_2O emission and the complexity of various factors involved in the process of soil N_2O production and emission. The greater production of N_2O under no ploughing corresponded to higher water contents near the soil surface than in the ploughed treatments (Fig. 2*a*). However, no-tilled soil was also accompanied by decreased diffusivity near the soil surface (Ball *et al.* 1999). Hence, the no-ploughing soil was likely to have been less aerobic than the ploughed soil but with restricted opportunities for gas escape. Under no-till, on the other hand, soil mineral N was lower than that under conventional tillage practice and such conditions were considered to inhibit N_2O emission from no-till soils (Liu *et al.* 2005). Furthermore, relationships between N_2O fluxes and dissolved organic C in soils where different preceding crop residues were incorporated, as well as between N_2O emission and crop residue C : N ratio, imply that crop residue might play an important role in N_2O emissions (Huang *et al*. 2004). The N_2O emissions were also related to the quantities of crop residue production under different ploughing practices. Higher N_2O emissions were observed for the 120-mm ploughing treatment which produced higher crop residues in the 2004 maize season (Tables 2 and 5). A previous investigation also indicated that root biomass from wheat stem elongation to flowering differed among various ploughing practices, and root biomass is closely correlated with soil nitrification rate (Chen and Huang 2006). Therefore, it is reasonable that root and stubble biomass can partly explain the variations in N_2O emission from wheat farmland under different ploughing practices (Tables 2 and 5).

Based on the calculated EF values under different treatments in Table 5, the coefficient of N_2O-N emission per kg fertiliser N applied per ha averaged 0.0213, a value consistent with the recent estimate of N_2O emissions from Chinese croplands using a precipitation-rectified emission factor (Lu *et al*. 2006). Our study also indicated that no-till tended to result in slightly higher EF values (Table 5). Although it is not easy to give a simple answer to explain the higher EF values in no-tilled plots, one possible explanation may be related with higher water content in no-tilled soil (Fig. 1 and Table 4).

Conclusion

Field observations indicated that the seasonal variation in soil respiration developed with a similar pattern for different treatments in each cropping season. This work demonstrates that ploughing depth can influence long-term loss of C from soil, but this was contingent on preceding cropping practice. Given the same preceding cropping practice, no significant difference in N_2O emission was found among different ploughing practices in each season. By keeping the N addition constant, the EF of nitrogen for N_2O depended on management practice (preceding cropping regime and ploughing practice). Our study indicated that no-till tended to result in higher EF values. Our study also suggested that further research on the interactions of tillage and residue management would be useful in elucidating recommended practices for reducing soil CO_2 and N_2O flux.

Acknowledgements

This study was supported by the National Natural Science Foundation of China (NSFC 40431001, 40605029). We thank Dawei Zhu, Chuanpo Niu, Zhenhua Lu, Yu Ouyang in Nanjing Agricultural University for their kindly help in gas sample collection. We greatly appreciate suggestions provided by anonymous reviewers, which improved the manuscript considerably.

References

Alvarez R, Alvarez CR, Lorenzo G (2001) Carbon dioxide fluxes following tillage from a mollisol in the Argentine Rolling Pampa. *European Journal of Soil Biology* **37**, 161–166. doi: 10.1016/S1164-5563(01)01085-8

Alvarez R, Diaz RA, Barbero N, Santanatoglia OJ, Blotta L (1995) Soil organic carbon, microbial biomass and CO_2–C production from three tillage systems. *Soil & Tillage Research* **33**, 17–28. doi: 10.1016/0167-1987(94)00432-E

Arah JRM, Smith KA, Crichton IJ, Li HS (1991) Nitrous oxide production and denitrification in Scottish arable soils. *Journal of Soil Science* **42**, 351–367. doi: 10.1111/j.1365-2389.1991.tb00414.x

Aulakh MS, Rennie DA, Paul EA (1984) Gaseous nitrogen losses from soils under zero-till as compared with conventional-till management systems. *Journal of Environmental Quality* **13**, 130–136.

Baggs EM, Chebii J, Ndufa JK (2006) A short-term investigation of trace gas emissions following tillage and no-tillage of agroforestry residues in western Kenya. *Soil & Tillage Research* **90**, 69–76. doi: 10.1016/j.still.2005.08.006

Ball BC, Scott A, Parker JP (1999) Field N_2O, CO_2 and CH_4 fluxes in relation to tillage, compaction and soil quality in Scotland. *Soil & Tillage Research* **53**, 29–39. doi: 10.1016/S0167-1987(99)00074-4

Carmo JB, Piccolo M, Andrade CA, Cerri CEP, Feigl BJ, Neto ES, Cerri CC (2007) Short-term changes in nitrogen availability, gas fluxes (CO_2, NO, N_2O) and microbial biomass after tillage during pasture re-establishment in Rondônia, Brazil. *Soil & Tillage Research* **96**, 250–259. doi: 10.1016/j.still.2007.06.002

Chatskikh D, Olesen JE (2007) Soil tillage enhanced CO_2 and N_2O emissions from loamy sand soil under spring barley. *Soil & Tillage Research* **97**, 5–18. doi: 10.1016/j.still.2007.08.004

Chen RH, Zhang Y, Chen RL, Ma ZH (2006) Effects of soil water content in ploughing layer on seedlings and growth of summer maize. *Journal Anhui Agricultural Science* **34**, 116–117. [in Chinese]

Chen ST, Huang Y (2006) Determination of respiration, gross nitrification and denitrification in soil profile using BaPS system. *Journal of Environmental Sciences (China)* **18**, 937–943.

Clayton H, Arah JRM, Smith KA (1994) Measurement of nitrous oxide emissions from fertilised grassland using closed chambers. *Journal of Geophysical Research* **99**, 16599–16607. doi: 10.1029/94JD00218

Crutzen PJ (1970) The influence of nitrogen oxides on the atmospheric ozone content. *Quarterly Journal of the Royal Meteorological Society* **96**, 320–325. doi: 10.1002/qj.49709640815

Du YL (2001) Investigation of the present status and development strategy for maize cultivation in Jiangsu Province. *Cultivation and Planting* **6**, 54–55. [in Chinese]

Franzluebbers AF, Hons FM, Zuberer DA (1995) Tillage-induced seasonal changes in soil physical properties affecting soil CO_2 evolution under intensive cropping. *Soil & Tillage Research* **34**, 41–61. doi: 10.1016/0167-1987(94)00450-S

Gesch RW, Reicosky DC, Gilbert RA, Morris DR (2007) Influence of tillage and plant residue management on respiration of a Florida Everglades Histosol. *Soil & Tillage Research* **92**, 156–166. doi: 10.1016/j.still.2006.02.004

He J, Li HW, Wang XY, McHugh AD, Li WY, Gao HW, Kuhn NJ (2007) The adoption of annual subsoiling as conservation tillage in dryland maize and wheat cultivation in northern China. *Soil & Tillage Research* **94**, 493–502. doi: 10.1016/j.still.2006.07.017

Helgason BL, Janzen HH, Chantigny MH, Drury CF, Ellert BH, Gregorich EG, Lemke RL, Pattey E, Rochette P, Wagner-Riddle C (2005) Toward improved coefficients for predicting direct N_2O emissions from soil in Canadian agroecosystems. *Nutrient Cycling in Agroecosystems* **72**, 87–99. doi: 10.1007/s10705-004-7358-y

Huang XX, Liu SP (1989) Effect of different tillage methods on soil compactness and growth of wheat root system. *Acta Agriculturae Shanghai* **5**, 61–66. [in Chinese, with English abstract]

Huang Y, Zhang W, Sun WJ, Zheng XH (2007) Net primary production of Chinese croplands from 1950 to 1999. *Ecological Applications* **17**, 692–701. doi: 10.1890/05-1792

Huang Y, Zou JW, Zheng XH, Wang YS, Xu XK (2004) Nitrous oxide emissions as influenced by amendment of plant residues with different C : N ratios. *Soil Biology & Biochemistry* **36**, 973–981. doi: 10.1016/j.soilbio.2004.02.009

Hunt PG (1996) Changes in carbon content of a Norfolk loamy sand after 14 years of conservation or conventional tillage. *Journal of Soil and Water Conservation* **51**, 255–258.

IPCC (2007) 'Climate Change 2007: The Physical Science Basis.' Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. (Cambridge University Press: Cambridge, UK)

Jia BR, Zhou GS, Wang FY, Wang YH, Yuan WP, Zhou L (2006) Partitioning root and microbial contributions to soil respiration in *Leymus chinensis* populations. *Soil Biology & Biochemistry* **38**, 653–660. doi: 10.1016/j.soilbio.2005.06.027

Kaharabata SK, Drury CF, Priesack E, Desjardins RL, McKenney DJ, Tan CS, Reynolds D (2003) Comparing measured and expert-N predicted N_2O emissions from conventional till and no till corn treatments. *Nutrient Cycling in Agroecosystems* **66**, 107–118. doi: 10.1023/A:1023978830307

Kuzyakov Y (2006) Sources of CO_2 efflux from soil and review of partitioning methods. *Soil Biology & Biochemistry* **38**, 425–448. doi: 10.1016/j.soilbio.2005.08.020

Lal R, Follett RF, Kimble J, Cole CV (1999) Managing U.S. cropland to sequester carbon in soil. *Journal of Soil and Water Conservation* **54**, 374–381.

Liu XJ, Mosier AR, Halvorson AD, Zhang FS (2005) Tillage and nitrogen application effects on nitrous and nitric oxide emissions from irrigated corn fields. *Plant and Soil* **276**, 235–249. doi: 10.1007/s11104-005-4894-4

Lu YY, Huang Y, Zou JW, Zheng XH (2006) An inventory of N_2O emissions from agriculture in China using precipitation-rectified emission factor and background emission. *Chemosphere* **65**, 1915–1924. doi: 10.1016/j.chemosphere.2006.07.035

MacKenzie AF, Fan MX, Cadrin F (1997) Nitrous oxide emission as affected by tillage, corn-soybean-alfalfa rotation and nitrogen fertilization. *Canadian Journal of Soil Science* **77**, 145–152.

Malhi SS, Lemke R, Wang ZH, Chhabra BS (2006) Tillage, nitrogen and crop residue effects on crop yield, nutrient uptake, soil quality, and greenhouse gas emissions. *Soil & Tillage Research* **90**, 171–183. doi: 10.1016/j.still.2005.09.001

Morris DR, Gilbert RA, Reicosky DC, Gesch RW (2004) Oxidation potentials of soil organic matter in Histosols under different tillage methods. *Soil Science Society of America Journal* **68**, 817–826.

Mosier AR, Halvorson AD, Reule CA, Liu XJ (2006) Net global warming potential greenhouse gas intensity in irrigated cropping systems in northeastern Colorado. *Journal of Environmental Quality* **35**, 1584–1598. doi: 10.2134/jeq2005.0232

Oorts K, Merckx R, Gréhan E, Labreuche J, Nicolardot B (2007) Determinants of annual fluxes of CO_2 and N_2O in long-term no-tillage and conventional tillage systems in northern France. *Soil & Tillage Research* **95**, 133–148. doi: 10.1016/j.still.2006.12.002

Pan GX, Li LQ, Wu LS, Zhang XH (2003) Storage and sequestration potential of topsoil organic carbon in China's paddy soils. *Global Change Biology* **10**, 79–92. doi: 10.1111/j.1365-2486.2003.00717.x

Pan GX, Li LQ, Zhang Q, Wang XK, Sun XB, Xu XB, Jiang DA (2005) Organic carbon stock in topsoil of Jiangsu Province, China, and the recent trend of carbon sequestration. *Journal of Environmental Sciences* **17**, 1–7.

Pan ZP, Xu XQ, Wu JM (1986) The applicability of no-tillage to rice-wheat/naked barley cropping system in Tai Lake region. *Journal of Agricultural Science* **2**, 1–7. [in Chinese, with English abstract]

Raich JW, Schlesinger WH (1992) The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. *Tellus* **44B**, 81–99.

Raich JW, Tufekcioglu A (2000) Vegetation and soil respiration: Correlations and controls. *Biogeochemistry* **48**, 71–90. doi: 10.1023/A:1006112000616

Reicosky DC, Archer DW (2007) Moldboard plough tillage depth and short-term carbon dioxide release. *Soil & Tillage Research* **94**, 109–121. doi: 10.1016/j.still.2006.07.004

Reicosky DC, Dugas WA, Torbert HA (1997) Tillage-induced soil carbon dioxide loss from different cropping systems. *Soil & Tillage Research* **41**, 105–118. doi: 10.1016/S0167-1987(96)01080-X

Reicosky DC, Lindstrom MJ (1993) Fall tillage method: Effect on short-term carbon dioxide flux from soil. *Agronomy Journal* **85**, 1237–1243.

Silver WL, Miya RK (2001) Global patterns in root decomposition: comparisons of climate and litter quality effects. *Oecologia* **129**, 407–419.

Wang YS, Wang YH (2003) Quick measurement of CH_4, CO_2 and N_2O emissions from a short-plant ecosystem. *Advances in Atmospheric Sciences* **20**, 842–844. doi: 10.1007/BF02915410

Wang ZQ, Zhang GP, Guo FQ, Chen XC (1985) Studies on wheat ecology: Relationship between the characteristics of growth and development of different ecotypes wheat cultivars and the climatic factors. *Acta Agriculturae Universitatis Zhejiangensis* **12**, 369–375. [in Chinese, with English abstract]

Weinhold B, Halvorson A (1998) Cropping system influences on several soil quality attributes in the northern Great Plains. *Journal of Soil and Water Conservation* **53**, 254–258.

Yung YL, Wang WC, Lacis AA (1976) Greenhouse effects due to nitrous oxide. *Geophysical Research Letters* **3**, 619–621. doi: 10.1029/GL003i010p00619

Zhang HL, Gao WS, Chen F, Zhu WS (2005) Prospects and present situation of conservation tillage. *Journal of China Agricultural University* **10**, 16–20. [in Chinese, with English abstract]

Zheng X, Han S, Huang Y, Wang Y, Wang M (2004) Re-quantifying the emission factors based on field measurements and estimating the direct N_2O emission from Chinese croplands. *Global Biogeochemical Cycles* **18**, GB2018. doi: 10.1029/2003GB002167

Zou JW, Huang Y, Lu YY, Zheng XH, Wang YS (2005) Direct emission factor for N_2O from rice–winter wheat rotation systems in southeast China. *Atmospheric Environment* **39**, 4755–4765. doi: 10.1016/j.atmosenv.2005.04.028

Manuscript received 3 December 2007, accepted 23 October 2008